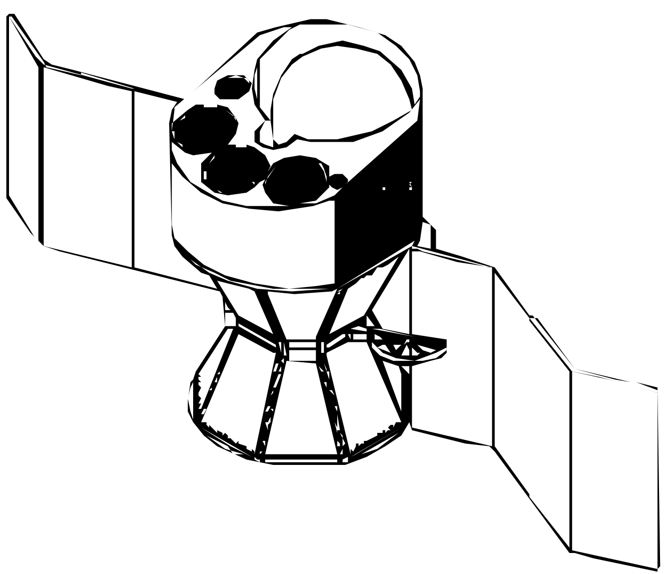
The Submillimeter Wave Astronomy Satellite (SWAS)



A Course for the Cooperative Satellite learning Project (CSLP) Technical Discussion Series

Fourth Quarter

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CHAPTER 1 – A BRIEF INTRODUCTION TO SWAS.

1.1. SCIENTIFIC GOALS FOR SWAS.

Stars, of which our Sun is a typical but very close example, are born amidst giant clouds of interstellar gas. Our galaxy, the Milky Way, is home to more than one hundred billion stars. Moreover, observations reveal the existence of billions of galaxies outside our own, each composed of billions of their own stars. This tells us that the conditions and forces that foster star formation must be present throughout the observable universe. Unfortunately, as common as this process appears to be, the exact steps that lead to a star being formed remain poorly understood. The instrumentation carried aboard NASA's Submillimeter Wave Astronomy Satellite (SWAS) is specifically designed to gather data on features of star formation.

During its mission lifetime, SWAS will observe hundreds of regions of ongoing star formation within our galaxy. The answers SWAS will provide are important not only to the understanding of the formation of future stellar systems, but also to the understanding of the processes that led to the formation of the Sun, the Earth, and the other planets and moons in our own solar system. To carry out its investigations, SWAS will detect radio emission from water (H_2O), molecular oxygen (O_2), isotopic carbon monoxide (^{13}CO), and atomic carbon (CI) (see the *Glossary of Terms* for a more detailed description of these terms), all of which emit at submillimeter wavelengths (i.e. 0.5-0.6 millimeters). Chemical models of interstellar gas clouds suggest that water and oxygen may be abundant species which, for reasons discussed later, affect the rate at which a cloud may release energy and, therefore, the cloud temperature. Since temperature affects the ability with which interstellar clouds are able to resist gravitational contraction, the abundances of water and oxygen will ultimately affect the process of star formation in interstellar clouds.

SWAS is the third mission in NASA's Small Explorer program (SMEX), which focuses on highly specialized and relatively inexpensive space science missions. Scheduled for launch on Oct 15, 1996, SWAS is an orbiting radio telescope which will study the chemical composition of interstellar clouds and, for the first time, map the abundances of oxygen and water in star forming regions. SWAS's science operations will be controlled by astronomers at the Smithsonian Astrophysical Observatory in Cambridge, MA.

1.2. THE NEED FOR A SPACE–BASED TELESCOPE.

Mauna Kea is a volcanic mountain on the Big island of Hawaii, and is considered by many to be one of the best astronomical observing sights in the world. The reason for this claim is that Mauna Kea is at an altitude of 14,000 feet, placing it above most of the water vapor in the Earth's atmosphere. The solid curve in Figure 1.1 is the *atmospheric transmission* (the amount of radiation from space which makes it through the Earth's atmosphere) for a very good night on Mauna Kea. The vertical dashed lines in Figure 1.1 plot the frequencies of the molecular lines which will be observed by SWAS. The interception between the dashed lines and the solid curve show whether or not the desired species will be observable from a high–altitude, ground–based telescope. For all the lines except [C I] (carbon), the atmospheric transmission at Mauna Kea is **zero**. This means that **none** of the light emitted from interstellar clouds makes it through the Earth's atmosphere. Even for [C I], the atmospheric transmission is only 0.4 (or 40%), meaning that only 40% of the interstellar light (at the frequency of carbon) that illuminates the Earth actually arrives at the summit of Mauna Kea. The remaining 60% is absorbed by the atmosphere. Since the Earth's atmosphere contains a great deal of water and oxygen, observations of these two species have been virtually impossible from ground–based telescopes, even from ones at high altitude. If we were to build a radio telescope at sea level, no emission from any of the desired molecular species would ever be detected because there is too much water vapor in the atmosphere. Therefore, to observe H_2O and O_2 we need to place a telescope well above the Earth's atmosphere. SWAS will accomplish this goal by orbiting the Earth at an altitude of 600 km.

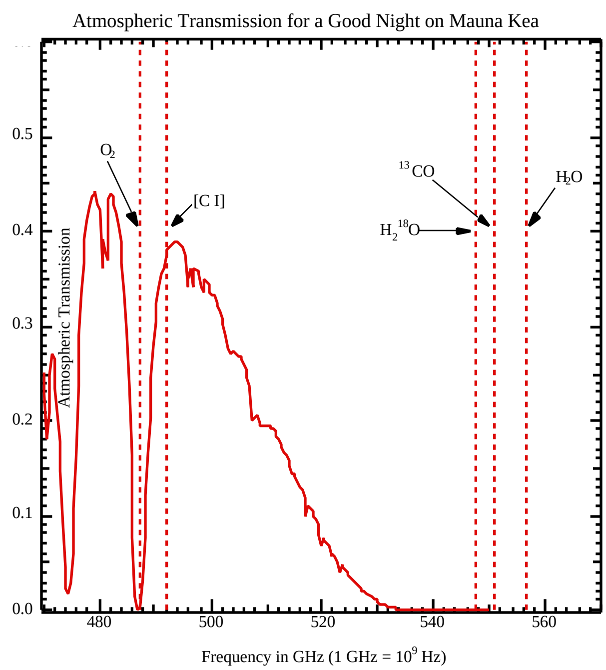


Figure 1.1 – Atmospheric transmission plot for a very good night on Mauna Kea. The solid line is the atmospheric transmission (i.e. the amount of radiation from space which makes it through the Earth's atmosphere). The dashed lines show if radiation with frequencies equal to the frequencies of the O_2, [C I], H_2O, $H_2{}^{18}O$, and ^{13}CO lines will be observable from Mauna Kea.

1.3. FOOD FOR THOUGHT – QUESTIONS FOR CHAPTER 1.

1) Given the following list of frequencies, which species will be observable (i.e. have an atmospheric transmission greater than 0.3) from Mauna Kea? (Hint – use Figure 1.1).

Species —	**Frequency** GHz
SO	487.7
CH_3OH	492.3
HCOOH	547.9
NO	551.2
CH_2CO	556.6

A – CH_3OH

2) Would you expect that a sea–level astronomical observatory would (generally speaking) be inferior or superior to one atop Mauna Kea? Why?

CHAPTER 2 – LIGHT & THE ELECTROMAGNETIC SPECTRUM.

2.1. THE BASICS.

Light is a phenomenon with many bizarre and unique properties. Some aspects of light can be best understood if it is thought of as being composed of infinitesimally small particles called photons. For example, the propagation of light through space can be visualized as large numbers of these photons moving from one point to another. Photons travel through space at 300,000 kilometers per second, known as the speed of light. The speed of light is often represented using the letter c, as follows:

$$c = 300{,}000 \text{ kilometers per second.}$$

According to Einstein's Theory of Relativity nothing can travel faster than the speed of light. This means c is the ultimate speed limit for everything in the universe. Another unusual property of photons is that they have no mass. In spite of this, photons can and do have energy, and the amount of energy, which varies greatly from photon to photon, can even be measured fairly easily. The concept that photons carry energy is an important one, and we will return to it in the discussion below. The particle-like properties of light are well-known. It is also true, however, that light has many other properties that are best understood if light is thought of as being a wave.

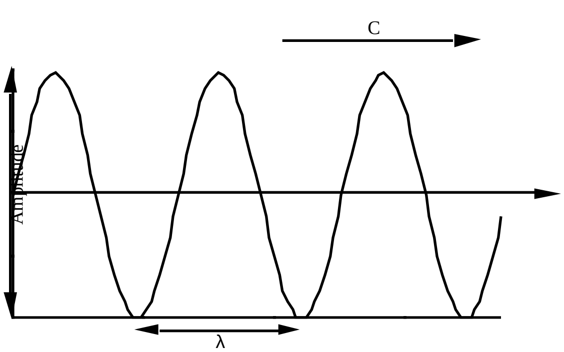


Figure 2.1 – A wave of light propagating through space. λ (pronounced "lambda") is the wavelength of the light wave. The light wave is traveling to the right at a speed of C also known as the speed of light.

When speaking of light as a "wave" we need a slightly different vocabulary. If you throw a pebble into a calm pond you create ripples in the water which travel outward as waves. A wave of light travels (or propagates) through space in a similar fashion. Figure 2.1 illustrates some of the properties of light as a wave. The light wave has a *wavelength* denoted by the Greek letter λ (pronounced "lambda") which is defined as the distance between two successive troughs (or crests) of the wave. Wavelength, therefore, is a unit of distance – like meters (or whatever unit you prefer to use). The wave also has an amplitude which is defined as the height of the crest. Instead of talking about the wavelength of the light wave we can also refer to its *frequency*. Frequency is defined as the number of wave crests which pass a given point in one second, and is usually written as the Greek letter ν (pronounced "nu"). The unit of frequency (number of wave crests which pass a given point in one second) has been named the *Hertz* (written as Hz) in honor of Heinrich Hertz, who first produced radio radiation. Perversely, radio astronomers usually refer to the frequency of light, whereas optical and infra–red astronomers usually talk about its wavelength. There is a simple relationship that allows one to convert from wavelength to frequency.

$$\boxed{c = \nu \times \lambda}$$

So multiplying the frequency (ν) times the wavelength (λ) yields the speed of light (c). Since c is a constant, given the wavelength you can always calculate the frequency (and vice–versa). Throughout this book we will use the terms wavelength and frequency interchangeably. You can also calculate the energy of a light wave by using another simple formula:

$$\boxed{E = h \times \nu}$$

Where E is the energy in ergs (an erg is a fundamental unit of energy). The quantity *h* is known as Planck's constant and is equal to 6.626 x 10^{-27} erg seconds . So the higher the frequency of the light, the smaller its wavelength, and the greater its energy.

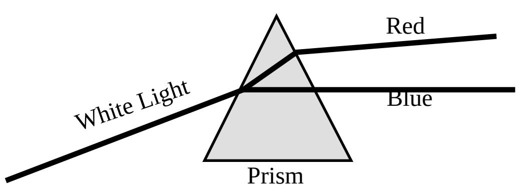


Figure 2.2 – A beam of white light being split into its component colors by a prism. As it travels through the prism, the blue light (with a smaller wavelength) is "bent" more than the red light (with a longer wavelength). Therefore, red light appears at the top and blue light appears at the bottom. The other colors fall in between.

Since light is a wave, with a frequency and an energy, it is simply a form of radiation. Visible light (the light we can see with our eyes) covers the wavelength range from $4x10^{-4}$ mm (blue light) to $7x10^{-4}$ mm (red light), and is the range of light you can see when you pass a beam of white light through a prism. In this experiment, the white light gets split up into a rainbow of colors – red, orange, yellow, green, & blue (see Figure 2.2). Blue light has more energy and a higher frequency (smaller wavelength) than red light so, it turns out, that the prism is simply sorting the light out by frequency.

However, the visible range of light (red through blue) is only a tiny portion of the entire *electromagnetic spectrum* (shown in Figure 2.3). Radiation with wavelengths greater than red light (λ = 0.0007 mm) is invisible to the naked eye. Light with wavelengths between approximately 0.0007 mm and 0.1 mm is known as *infrared* radiation. If the wavelength exceeds 0.1 mm then we enter the regime of radio waves. On the other side of the spectrum, radiation with wavelengths less than that of blue light

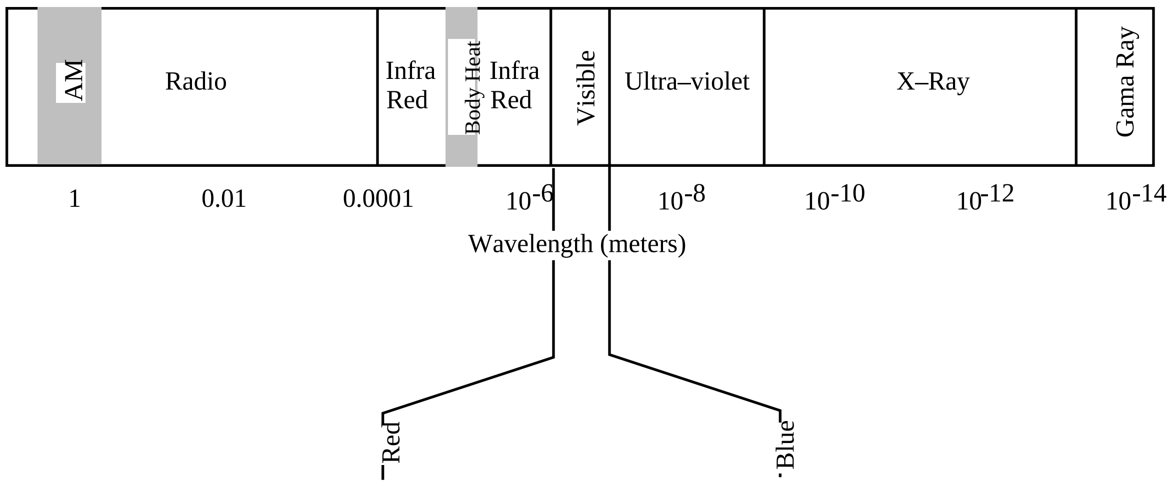


Figure 2.3 – An illustration of the electromagnetic spectrum. Note that the spectrum does not end at λ = 1m or at $\lambda = 10^{-14}$ m, but continues on indefinitely in both directions.

(λ = 0.0004 mm) is also invisible to the naked eye. Light with wavelengths between approximately 0.0004 mm and $1\text{x}10^{-6}$ mm is known as *ultra–violet* radiation. From $\lambda = 1\text{x}10^{-6}$ mm to $1\text{x}10^{-10}$ mm is the X–ray regime, and if the radiation has a wavelength less than $1\text{x}10^{-11}$ mm it is called gamma–rays.

2.2. SPECTRAL LINES.

One of the great successes of modern astronomy is the ability of researchers to identify the chemical components (atoms and molecules) of most astronomical objects, without ever having to be in direct contact with a nebula, star, or galaxy. This makes it possible to compare the chemical composition of, say, the sun, to other stars. This is crucial for the SWAS mission, since it allows us to make chemical comparisons between different molecular clouds. It has many profound consequences, which will be discussed in the following sections. In this section we will describe how these identifications are made.

It is a fact of nature that radiation emitted by neutral atoms and molecules does not occur at any random frequency (or wavelength). Instead, both atoms and molecules emit light at a small number of frequencies, **and no others**. These frequencies are particular to the emitting species, and **no two species are alike**. This concept is illustrated in Figure 2.4 for the element hydrogen. Hydrogen consists of one electron orbiting around a nucleus composed of a single proton (like a satellite orbiting around the Earth). The distance between the orbiting electron and the nucleus (or the satellite and the Earth) is proportional to the energy of the orbit (the greater the distance, the higher the energy), therefore we usually refer to the various orbits of the electron as *energy levels*. However, in contrast to a satellite which can orbit at any altitude and thus attain any energy level, the electron is only allowed to orbit in very specific energy levels. This is what is meant when one says that the electron's energy levels are *quantized*, and is one of the fundamental rules of atomic physics. In general, the electron will be orbiting in level 1 (also called the *ground state*), which is where the electron always "wants" to be, but the electron could conceivably be orbiting the nucleus in any one of an infinite number of discrete energy levels.

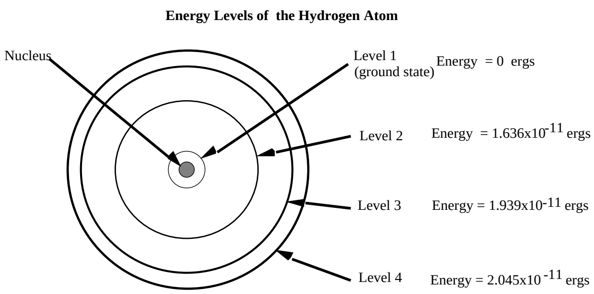


Figure 2.4 – An illustration of the four lowest energy levels of the Hydrogen atom. There are actually an infinite number of these energy levels with energies up to 2.18x10^{-11} ergs, at which point the atom is ionized (i.e. the electron is stripped completely off the atom). An electron can "jump" from any level to a higher energy level if it is hit by a photon with exactly the right energy, otherwise the photon is ignored. The photon energy required to excite an electron from some random level X to another random level Y is equal to the energy of level Y minus the energy of level X.

Suppose a hydrogen atom is located somewhere in interstellar space. It will continuously be colliding with other atoms (and also with molecules if they are present,)and will be occasionally struck by a photon coming from a light source, like a star. When a photon strikes a hydrogen atom, one of three things can happen.

1.) The photon will have so much energy that it knocks the electron off of the atom, leaving an ionized hydrogen atom behind.

2.) If the photon's energy **exactly matches** the energy difference between two levels in the hydrogen atom, the photon will be absorbed by the atom. When this happens, the atom acquires the energy once carried by the photon, and the electron "jumps" to a higher energy state. This process is called excitation. After a very short period of time the electron, which "wants" to get back to the ground state, will spontaneously "jump" back to some allowed lower energy level. The new level may be the level from whence the electron originally came, or it may be any other allowed lower energy level. In jumping from a higher level to a lower level, the electron emits a photon with an energy exactly equal to the energy difference between the two levels. This process is called *de–excitation*. Figure 2.5 illustrates the processes of excitation and de–excitation.

3.) If the incoming photon does not have the right amount of energy to exactly match the difference in the atom's energy levels, the atom and photon will ignore each other completely. The photon will continue on as if the atom wasn't even there.

For example, if the hydrogen atom's electron is in the ground state (level 1), and the incoming photon has **exactly** 1.636×10^{-11} ergs of energy (equal to the energy of level 2 minus the energy of level 1), the photon will be absorbed and the electron will "jump" from level 1 to level 2. After a very short period of time, the electron will spontaneously "jump" back to the ground state, re–emitting a photon with **exactly** 1.636×10^{-11} ergs of energy. The electron can jump between any two levels (i.e. from level 1 to level 3, or from level 1 to level 44, etc.). The electron can even jump between excited levels (i.e. from level 2 to level 3) if it absorbs a photon of exactly the right energy (i.e. equal to the energy of level 3 minus the energy of level 2) before the electron spontaneously jumps back to the ground level.

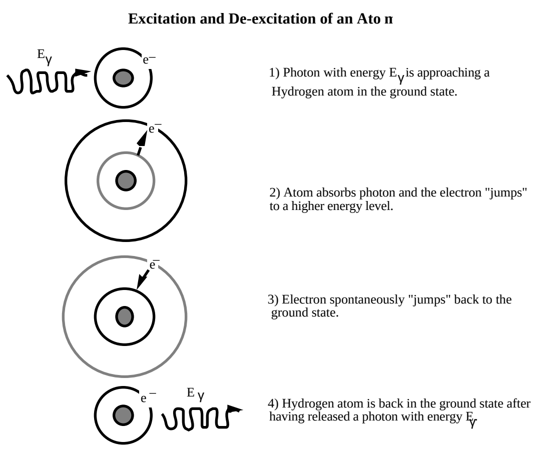


Figure 2.5 – An illustration of the processes of excitation and de-excitation in an atom.

Electron Jumps from this Level	To this Level	Wavelength of Emitted Photon (in cm)
2	1	$\lambda = 1.215\text{x}10^{-5}$
3	2	$\lambda = 6.562\text{x}10^{-5}$
4	3	$\lambda = 1.8751\text{x}10^{-4}$

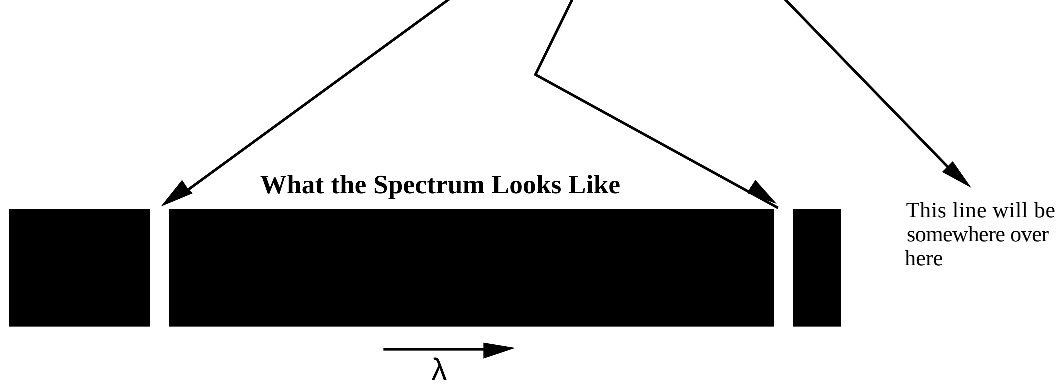


Figure 2.6 – An illustration of a few of the spectral lines that can be observed from Hydrogen gas as the electrons get de–excited. The first column of the table indicates the higher energy level (in which the electron initially orbits). The second column indicates the lower energy level to which the electron spontaneously "jumps" (de–excites). The third column indicates the wavelength of the photon emitted from the atom as a result of the de–excitation (remember a photon's energy and wavelength are related!).

Since the process of de–excitation releases photons with only certain energies, if we examine the electromagnetic spectrum produced by a container full of excited hydrogen gas (using a prism or other such device), we will observe a series of bright, narrow lines, called *spectral lines*. Figure 2.6 illustrates a few of the spectral lines that can be observed from Hydrogen gas as the electrons get de–excited.

Since every atom or molecule undergoes the processes of excitation and de-excitation from discrete energy levels, every atom or molecule will produce a series of spectral lines. In addition, **no two atoms or molecules will have the same set of spectral lines**. The spectral lines produced by a particular atom or molecule are its "spectral fingerprints" that uniquely identify it. Therefore, by comparing the spectral lines emitted by an astronomical object with those emitted by a known substance (measured in a laboratory), astronomers routinely determine the chemical composition of interstellar gas and of stars. For example, by examining the spectra of stars, astronomers have learned that stars are composed of Hydrogen, helium and a number of other chemical species.

2.3. FOOD FOR THOUGHT — QUESTIONS FOR CHAPTER 2.

1) The frequency of the neutral carbon line is 492.1607 GHz. What is its wavelength? (1 GHz = 10^9 Hz). *A – 0.0609 cm or 0.609 mm.*

2) Which has a longer wavelength : a wave with a frequency of 100 MHz or a wave with frequency 100 GHz? *A – the wave with ν = 100 MHz has a longer wavelength.*

3) Which are more energetic: X-rays or radio waves? *A – X-rays*

4) What is the energy (in ergs) of a wave with frequency 100 GHz? of 100 THz? (1 THz = 1 Terrahertz = 10^{12} Hz).

Answer

frequency **Hz**	**Energy** **ergs**
100×10^{9}	6.626×10^{-16}
100×10^{12}	6.626×10^{-13}

5) What are the frequencies of the Hydrogen lines listed in Figure 2.5?

Answer

wavelength **cm**	**frequency** **Hz**
1.215×10^{-5}	2.47×10^{15}
6.562×10^{-5}	4.57×10^{14}
1.8751×10^{-4}	1.6×10^{14}

6) What energy must a photon have to cause a hydrogen atom's electron to jump from level 2 to level 3? What is the wavelength of this photon? *A – Energy = 3.029×10^{-12} ergs. Wavelength = 6.562×10^{-5} cm.*

7) What is the wavelength of a photon emitted when a hydrogen atom's electron jumps from level 4 to level 2?

A– $E = E_4 - E_2 = 2.045x10^{-11} - 1.636x10^{-11} = 4.09x10^{-12}$ *ergs.*

and $E = h\nu = hc/\lambda$.

Therefore $\lambda = hc/E = (6.626x10^{-27} \text{ x } 3x10^{10})/4.09x10^{-12} = 4.860x10^{-5}$ *cm.*

CHAPTER 3 – THE BASICS OF STAR FORMATION.

3.1. AN OVERVIEW OF MOLECULAR CLOUDS.

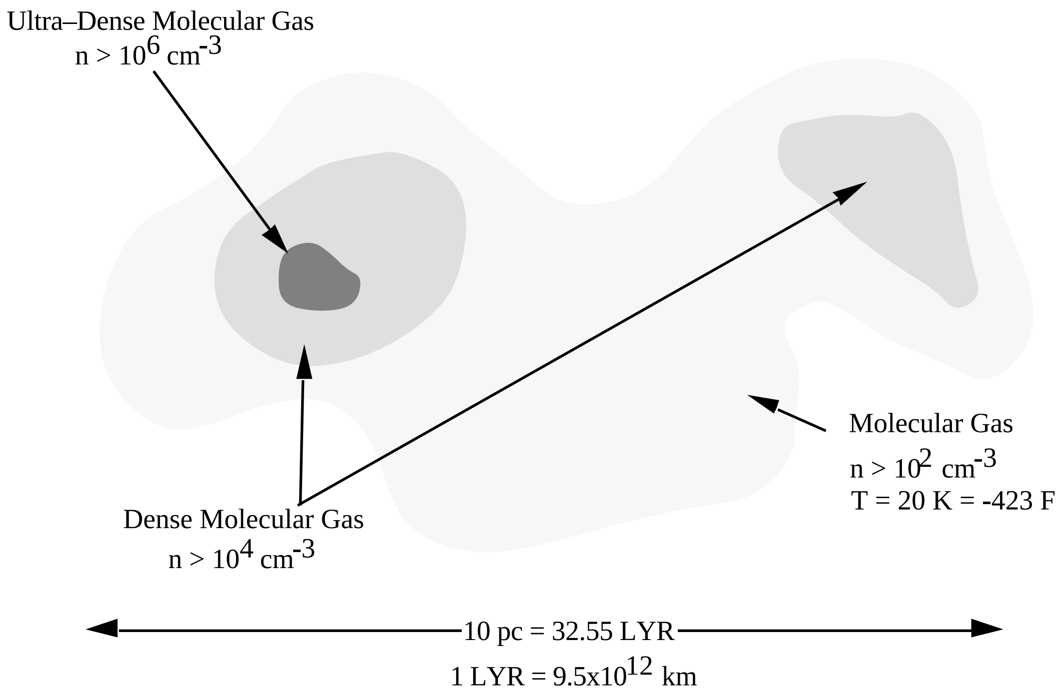
The plane of our galaxy is composed of millions of stars along with the gas and dust from which the stars form. The gas and dust in the galaxy, often labeled as the interstellar medium (ISM), is unevenly distributed over large regions of the galaxy forming complexes of massive condensations, whose molecular hydrogen densities are greater than 100 particles per cubic centimeter (written as $n(H_2) > 100\ cm^{-3}$), embedded in a patchy sea of low density ($n(H_2) < 10\ cm^{-3}$) atomic material. It is in these condensations that molecules form, leading astronomers to label the dense regions of the ISM as *molecular clouds*.

Molecular clouds are irregularly shaped objects that are spread over tens of parsecs (1 parsec ~ 3.086×10^{18} cm) and contain enough material to build over a million solar systems such as our own. Within a single cloud there is even more structure with each cloud containing dense ($n(H_2) > 10^4\ cm^{-3}$) gas cores, surrounded by the more extended lower density ($n(H_2) \sim 100\ cm^{-3}$) molecular cloud. This structure is illustrated in Figure 3.1, where small denser cores are shown embedded within a larger cloud. It is important to note that gas which is considered dense by interstellar standards, is still more rare than the best vacuums we can achieve in the laboratory.

The structure of an interstellar gas cloud, however, is much more complex than can be described by a simple cartoon like Figure 3.1. Real interstellar clouds look very much like Terrestrial clouds – containing dense clumps, filamentary structures, fluffy billowing tendrils etc. Figure 3.2, which is a picture of a well-known region in Orion called the Horsehead nebula and Figure 3.3, which is a picture of the Eagle Nebula (M16) recently taken by the *Hubble Space Telescope* (HST), illustrate this concept quite clearly. Both figures are optical images, meaning that the light falls in the visible range of the electromagnetic spectrum (i.e. you can see this light with your eye). The glowing gas is primarily atomic hydrogen. These same regions, however, also emit strongly in invisible radio wavelengths, indicating the presence of a significant amount of molecular gas. Figure 3.4 compares the optical emission from a small portion of Figure 3.2 with Carbon Monoxide (CO) emission, which has a frequency of 230 GHz. Figure 3.4 shows that there is plenty of molecular gas (as traced by the CO emission) in regions devoid of optical emission (e.g. between region #1 and region #4). Furthermore, extended observations of CO have shown that molecular gas exists far beyond the boundaries of Figure 3.2.

The prime candidates for SWAS observations are the denser regions of Giant Molecular Clouds (called *giant cloud cores*), as well as another type of interstellar gas cloud, called *dark cloud cores*. Giant molecular cloud cores are regions of high density ($n(H_2) > 10^4$ cm^{-3}) and warm temperature (T ~ 35 K = –238 ˚C), located within the much larger, lower density extended cloud (see Figure 3.1). Note that astronomers call these regions “warm” even though the temperatures are 35 ˚K! This is because they **are** warm relative to interstellar space. These cores have diameters of ~ 1 parsec and are generally associated with sites of massive star formation (i.e. stars which are 5 to 20 times more massive than the Sun). These massive stars are intrinsically hot and energetic, and react with the surrounding gas (in which the star formed) producing complex chemical reactions. Dark cloud cores are also sites of high density situated within a larger extended cloud. However, these cores are, in general, smaller (diameter ~ 0.3 pc), colder (T ~ 10 K), and less dense ($n \sim 10^4$ cm^{-3}) than their giant cloud counterparts. In addition to being smaller, dark cloud cores do not form as many massive stars as giant cloud cores and therefore contain more pristine molecular material, material which has not been affected by the formation of stars.

A "Typical" Giant Molecular Cloud



GMC mass ~ 10^5 solar masses (M_o)

Figure 3.1 – Schematic diagram of a Giant Molecular Cloud (GMC). Real GMC's are irregularly shaped with numerous "knots" of higher density. The structure of a GMC is very much like that of a cloud in the Earth's atmosphere, except that a GMC is much, much larger.

Figure 3.2 – (Next Page) Optical image of a well–known region in Orion called the Horsehead nebula. The glowing gas is primarily atomic Hydrogen. The numbers indicate the following regions: (1) Glowing hydrogen gas in the nebula NGC 2024. This gas is glowing via the process of de–excitation. The gas in NGC 2024 is quite dense, with certain regions having densities in excess of 10^5 cm^{-3}. (2) A dark lane of dust (small non–gaseous, solid particles composed of graphites and silicates). The dark patch **does not** indicate an absence of glowing hydrogen gas. In reality, the dust lane lies in front of the glowing gas, thereby obscuring the light originating behind it. (3) The massive, hot star Zeta - Ori. This star provides much of the ionizing energy in this region of Orion. (4) Hydrogen gas in the nebula NGC 2023. This gas is not glowing via de–excitation like the gas in NGC 2024, but is reflecting the light from Zeta – Ori. (5) Glowing hydrogen gas of lower density than that in NGC 2024. (6) The Horsehead Nebula – composed of a dark dust lane obscuring the glowing gas behind it. If you use your imagination, you can picture this dark patch as a horse's head. This region of Orion is 415 pc from Earth. Therefore, the distance between region #1 and region #6 is 3 pc, or 15,866 times larger than our entire Solar system.

Figure 3.3 – (Page after Next) Optical image of the Eagle nebula (also known as M16). This picture was taken by the *Hubble Space Telescope* and beautifully illustrates the cloud–like nature of interstellar gas clouds.

Figure 3.4 – (2nd Page after Next) (Left) Blow–up of the NGC 2024/2023 region of the Horsehead nebula as seen in Figure 3.2. (Right) Emission from the CO (carbon monoxide) molecule from the NGC 2024/2023 region. The numbering system is the same as that used in Figure 3.2. Notice how there is a significant amount of molecular gas (as traced by the CO emission) in regions devoid of visual emission (i.e. between region #1 and region #4). In addition, notice that the dust lane (region #2) has essentially disappeared in the map of CO emission. This is because the radio waves, emitted from the gas behind the dust lane, can pass through the dust lane unhindered. This is similar to what would happen if you entered a closet with no windows. No light from outside can enter, but you could still listen to a portable radio. This is because the walls and doors of your house are opaque to visible light, but not to radio waves.

3.2. STAR FORMATION THROUGH CLOUD COLLAPSE.

Since the density inside a star is many times greater than the average density of a molecular cloud, astronomers theorize that, for unknown reasons, portions of the low density molecular cloud collapse to form cores, which then provide the building blocks for star formation.

Focusing in on the dense ($n(H_2) > 10^4\ cm^{-3}$) gas part of the molecular cloud, we see that there is even more sub–structure to the cloud: "ultra–ultra dense clumps" whose densities may exceed $n(H_2) = 10^7\ cm^{-3}$ (Figure 3.5). These "ultra–ultra dense clumps" are quite small by astronomical standards – greater than 0.005 pc in diameter. Triggered by an as yet unknown event or series of events, gravity's pull overcomes the random gas motions within a small clump, initiating a contraction phase (Stage #1 in Figure 3.6). However, since the molecular clouds and clumps almost always have a small amount of rotation, as the clumps collapse, they begin to spin faster (think of a spinning figure skater. If he tucks in his arms, he spins faster). The result is that the collapsing clump begins to deform, flattening at the poles to produce a disk of spinning gas. At the center of the disk, however, the collapse towards stellar birth continues. During this collapse phase, the gas density increases, collisions between atoms and molecules become more frequent and the gas temperature rises (Stage 2 in Figure 3.6). At this stage we have a *proto–star* at the center of the disk. A proto–star differs from a real star in that the process of nuclear fusion, which powers a real star, has not yet begun.

Because the extent of the collapse is immense - more than a factor of 10 million from diffuse gas to star - the resulting gas temperature increases from about 15 degrees

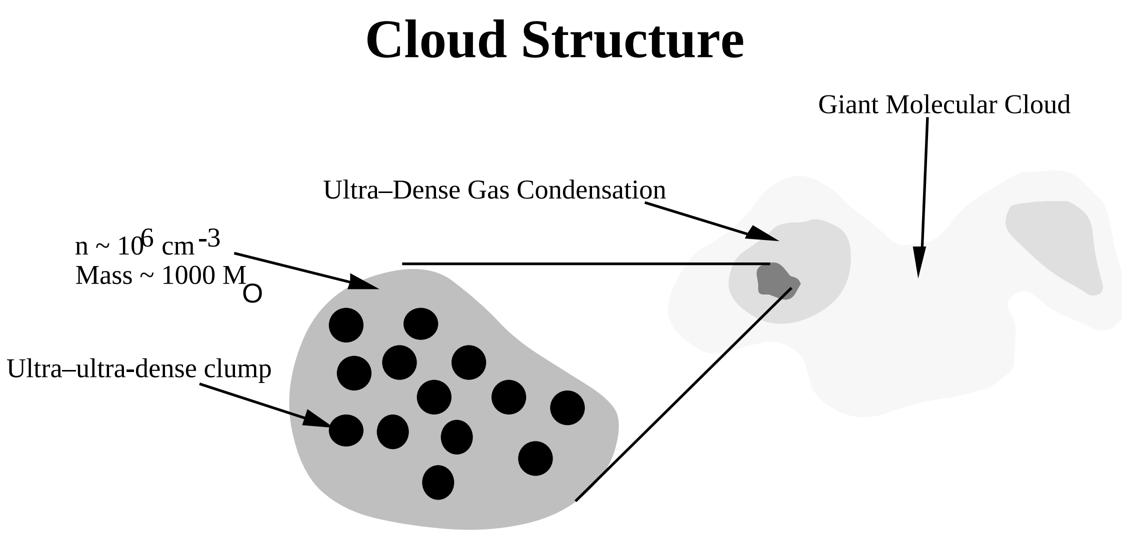


Figure 3.5 – A cartoon diagram illustrating some sub–structure in molecular clouds. The giant cloud core seen in Figure 3.1 has been blown–up to reveal numerous "ultra–ultra dense clumps". It is these "ultra–ultra dense clumps" that might eventually form stars.

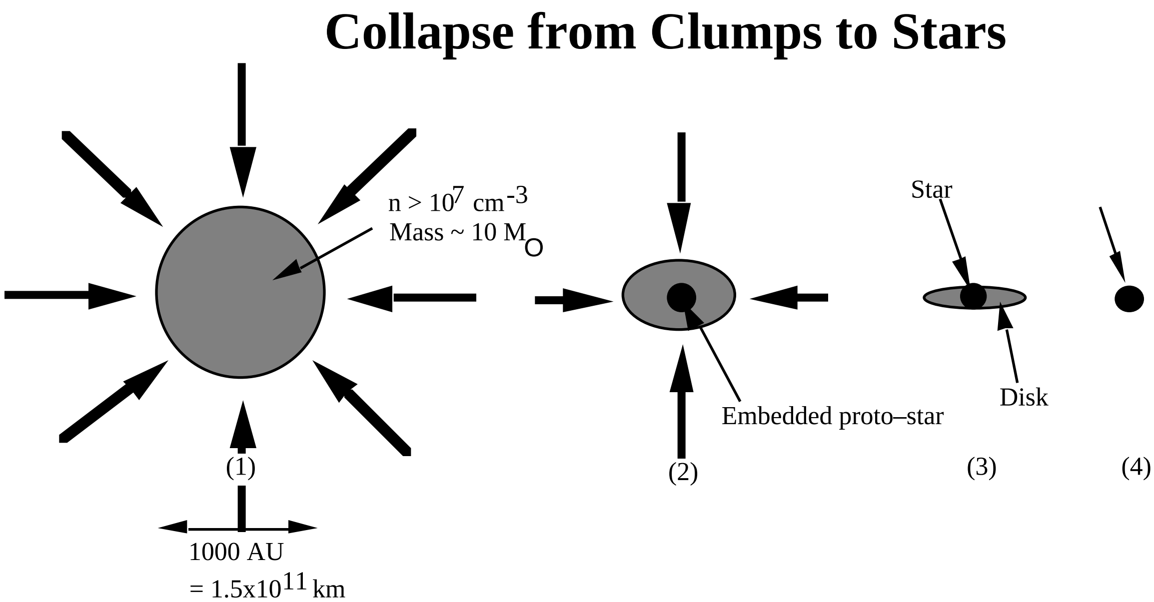


Figure 3.6 – A cartoon diagram describing the basic concept of star formation through clump collapse. (1) One of the "ultra–ultra dense clumps" (as seen in Figure 3.5) begins to collapse under the force of its own gravity. (2) Collapse continues but, because the clump is spinning, the clump begins to flatten like spinning pizza dough. The object in the middle of the disk is a *proto–star* – hot, high density gas which has not yet initiated nuclear fusion. (3) The temperatures and densities in the proto–star are high enough that nuclear fusion has begun. At this stage we have an actual star (no longer a proto–star) embedded in its natal disk of gas. (4) After time the disk surrounding the star evaporates, leaving a naked star. Note – 1 AU is an Astronomical Unit – the average distance between the Earth and the Sun.

Kelvin to over 11 million degrees Kelvin . Once temperatures this high are reached, the gas is able to initiate nuclear fusion (fusing hydrogen atoms into helium to produce energy) and the star is born! (Stage 3 in Figure 3.6). Over the next million years or so, radiation from the star gradually destroys the surrounding disk, eventually leaving a naked star (Stage 4 in Figure 3.6). From the onset of collapse, to the actual stellar birth, the entire process takes about 10,000 to 10,000,000 years, depending on a number of factors such as mass, density, and temperature.

Although the theory of star formation is quite complex, it boils down to a battle between pressure (which is supporting the clump against collapse) and gravity (which is causing the clump to collapse). In the absence of all other forces a clump would simply collapse under the force of its own gravity. However, clumps do not exist in the absence of other forces – they all have a certain amount of internal pressure (see Figure 3.7). Gas pressure is simply the force exerted by a group of molecules as they collide with each other (or with the walls of a gas container). Therefore, as the gas density increases, more collisions occur, and the pressure increases. Also, as you increase the temperature, the energy of the collisions between molecules increases, and therefore the pressure also increases. Conversely, if you increase the pressure and density of a gas, the temperature will rise. This is why the temperatures in the interior of a collapsing clump can rise so dramatically (i.e. from 20 K to 11 million K!).

There is a fairly simple equation which can be used to estimate the mass needed in order to overcome the internal pressure of a clump and initiate collapse. The quantity:

$$M_J = 100\left(\sqrt{T/10}\right)^3 \sqrt{1000/n}$$

is the mass (in units of solar masses; $M_\odot$) that is required for a clump of gas to begin to collapse under the force of its own gravity. This mass (M_J) is called the *Jeans's Mass* after the astronomer who first developed the idea. *T* is the temperature of the gas (in Kelvin) and n is the density of the gas (i.e. n(H_2) in particles per cubic centimeter). The following three examples illustrate how the Jean's Mass changes with different physical conditions.

Example 1 – T = 20 K, n = 100 cm^{-3}
M_J = 894 $M_\odot$

Example 2 – T = 100 K, n = 100 cm^{-3} M_J = 10,000 $M_\odot$

Example 3 – T = 20 K, n = 10^6 cm^{-3}
M_J = 8.9 $M_\odot$

From these examples we can see that a cold, dense clump (Example 3) can begin collapsing as long as it contains at least 8.9 solar masses worth of gas (similar to the 10 $M_\odot$ "ultra-ultra dense clumps"). On the other hand, a hot, low density clump (Example 2) requires a gas mass of at least 10,000 solar masses before it can overcome its internal pressure and begin collapsing. Therefore, star formation is more likely to occur in a cold, dense clump, since it has a small Jean's Mass.

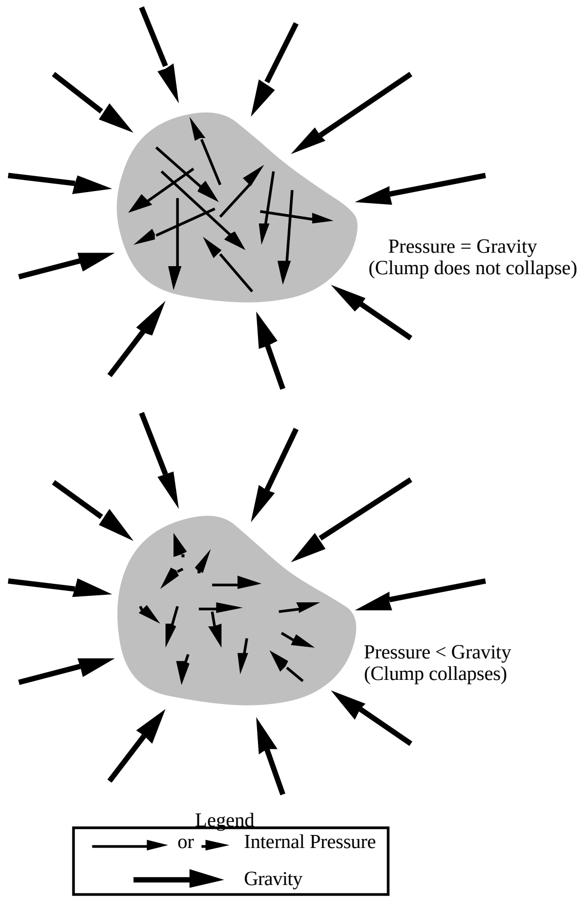


Figure 3.7 – A demonstration of internal cloud pressure versus gravity. In the top figure the internal cloud pressure (illustrated by the thin arrows) is equal to the force of gravity (illustrated by the thick arrows). Therefore, the force trying to expand the cloud (pressure) equals the force trying to collapse the cloud (gravity), and the cloud remains unchanged. In the bottom figure the internal cloud pressure is less than the force of gravity. Therefore, the force trying to expand the cloud (pressure) is less than the force trying to collapse the cloud (gravity), and the cloud collapses.

3.3. THE EFFECT OF HEATING & COOLING ON CLOUD COLLAPSE.

As can be seen from the discussion on the Jean's mass, star formation is governed by **two** dominant influences: gravity and pressure. As mentioned earlier, during the collapse phase of star formation, the gas pressure and density increases, collisions between atoms and molecules become more frequent and the gas temperature will increase. However, the heating of the collapsing cloud poses a problem; since a heated gas wants to expand, the cloud collapse could be halted or even reversed unless heat is effectively and continuously removed from the cloud.

As mentioned earlier, collisions between molecules will heat the gas. However, under certain conditions, collisions between molecules can also help to significantly cool the gas. When two molecules collide, they convert some of their thermal (kinetic) energy into a form of potential energy by leaving one or both of the molecules in an excited electronic state. These molecules can then de-excite by emitting a photon. This process is similar to that which occurs in a simple Hydrogen atom where, due to an input of energy (like a collision) an electron "jumps" from a low energy level to a higher energy level. However, the higher energy orbits are intrinsically unstable so the electron "wants" to return to the lowest possible energy level. As the electron jumps to a lower energy level, the atom emits energy in the form of a photon of light (see Figure 3.8). Photons that escape the cloud carry this energy with it, thus helping to cool the cloud. Note that this process is very similar to the excitation (and de–excitation) of atoms described in Ch. 2.

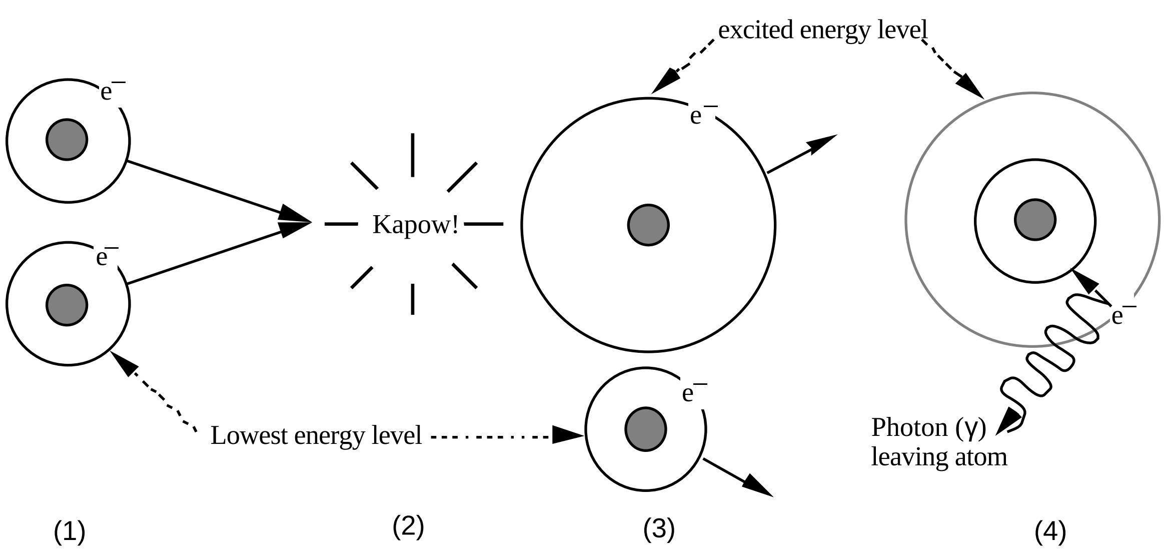


Figure 3.8 – Illustration of how collisions between two atoms (or molecules) can cause cooling of the interstellar gas. **(Step 1)** Two atoms with electrons in the lowest energy level approach each other at equal speeds. **(Step 2)** The atoms collide. **(Step 3)** The atoms separate after collision. The atom on the bottom has its electron in the same energy level as before but the atoms speed has been reduced. The atom on top, however, has absorbed enough energy from the collision to cause its electron to jump to a higher energy level. **(Step 4)** The electron spontaneously jumps back to its initial (lowest) energy level producing a photon of light (γ - pronounced "gamma"). The energy of γ is equal to the difference in energy between the two levels. If the photon escapes the cloud then cooling has occurred.

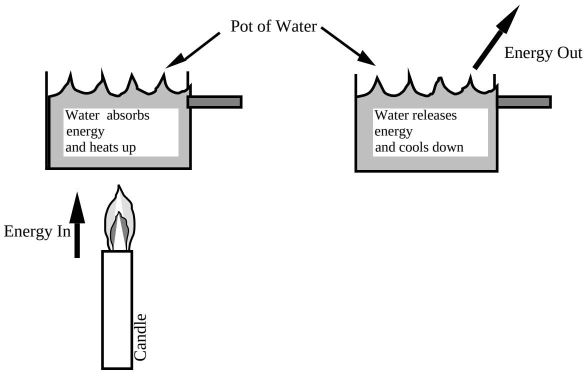


Figure 3.9a – Illustration of the heating and cooling process in a pot of water. The water is simultaneously being heated by the flame and being cooled by various processes like the release of steam and infra–red radiation. If the amount of energy put into an object is greater than the amount of energy released from the object, the object will heat up. If the amount of energy put into an object is less than the amount of energy released from the object, the object will cool.

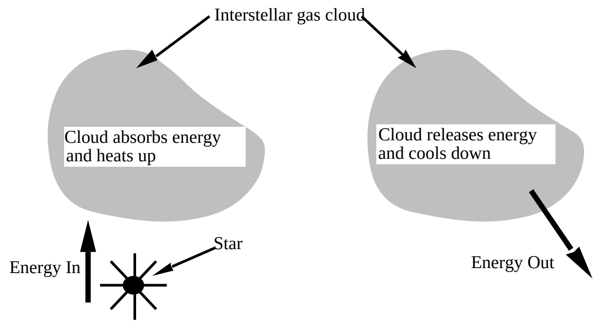


Figure 3.9b – Illustration of the heating and cooling process in an interstellar gas cloud. The cloud is simultaneously being heated by radiation from the star and being cooled by various processes like collisional excitation followed by spontaneous de–excitation (as in Figure 3.8).

Atoms and molecules are considered to be good coolants if: (1) they readily emit photons following a collision and (2) they are present in large enough quantities that a significant number of photons are emitted (i.e. so that many collisions like that illustrated in Figure 3.8 occur). In this way the collapse of an interstellar cloud is tied to the chemical composition of that cloud. It is important to note that it is the photons produced by the process of collisional excitation followed by a spontaneous de–excitation (the process illustrated in Figure 3.8), that will be observed by SWAS.

However, for cooling to occur, the photons emitted by de–excitations following collisions (the process illustrated in Figure 3.8) must escape the gas cloud. Figure 3.9a shows a familiar process in which a flame (or stove top) heats up a pot of water. If we leave the flame on long enough, the water eventually comes to a boil. However, the temperature of the boiling water does not continue to increase indefinitely because, at the same time the water is being heated, it is also cooling (in the form of steam, infra-red radiation etc.). The same process occurs in interstellar gas clouds, except that instead of a flame heating a pot of water, we have a star heating a cloud of gas (Figure 3.9b). Basically, if the amount of energy put into an object is greater than the amount of energy released from the object, the object will heat up. If the amount of energy put into an object is less than the amount of energy released from the object, the object will cool.

Hydrogen and helium are, by far, the most abundant elements in interstellar clouds but they are very poor coolants because they cannot be collisionally induced to emit photons at the low gas temperatures characteristic of molecular clouds. Theoretical studies going back two decades have predicted that a large fraction of the total cooling is borne by a few other atoms and molecules, notably gaseous water (H_2O), carbon monoxide (CO), molecular oxygen (O_2), and atomic carbon (C). However we currently have little or no information on the abundance of either water or molecular oxygen, because the photons of these important species are blocked by the Earth's atmosphere. Water is believed to be a good coolant at high temperatures because theoretical models of the chemistry have predicted that its abundance will undergo a dramatic increase at higher temperatures. Figure 3.10 shows a recent calculation of the contribution water and other key species to cooling of the interstellar medium.

Figure 3.10 demonstrates that at lower densities and temperatures CO and O_2 are the dominant coolants but at high densities a host of molecules, under the heading "other molecules", add up their contributions to dominant the cooling. However, at higher densities and temperatures water becomes the principle coolant. These conditions can be expected to occur when interstellar clouds collapse. Thus the theory predicts that, during the process in which every star has formed, the collapsing cloud must pass through a phase in which the currently unobservable water molecule is the dominant coolant.

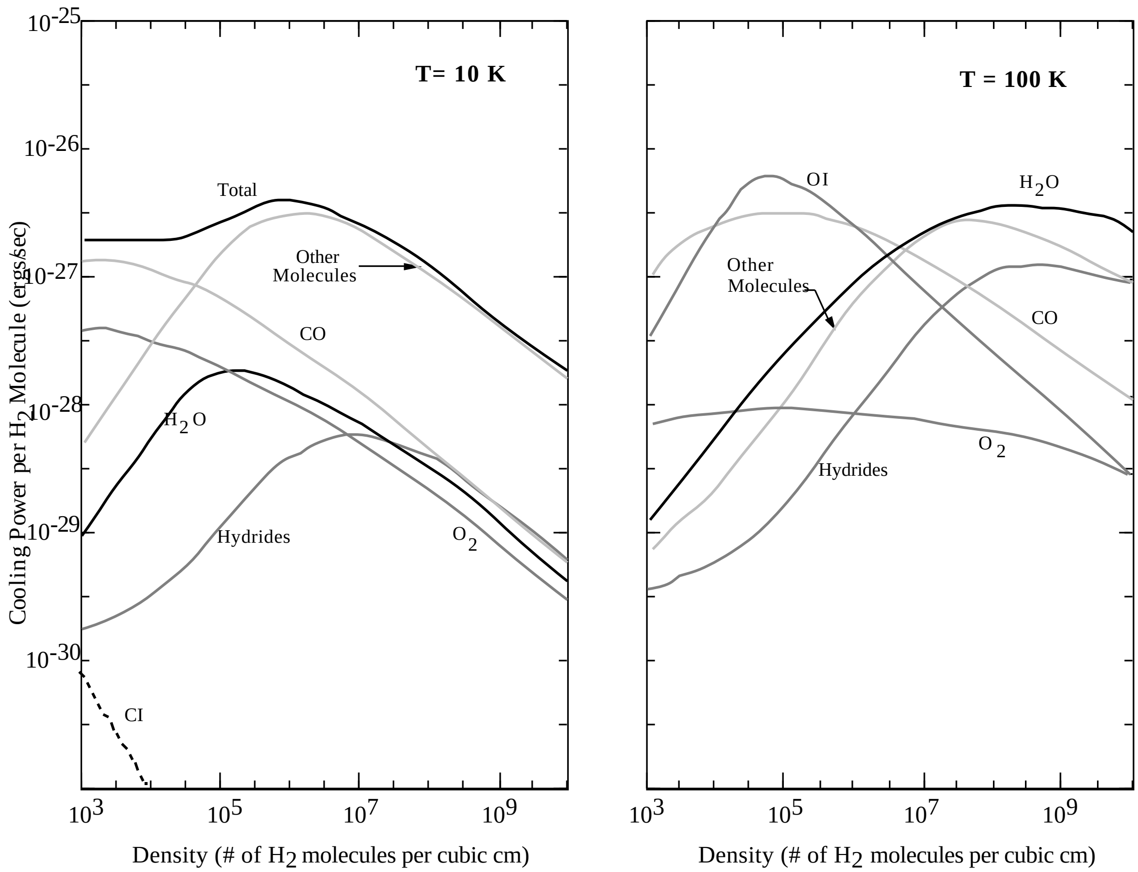


Figure 3.10 – Cooling curves (cooling as a function of the density of the most abundant molecule, molecular hydrogen H_2) computed for the conditions expected in interstellar clouds prior to the formation of a star.

3.4. FOOD FOR THOUGHT — QUESTIONS FOR CHAPTER 3.

1) If the solar system is 39.5 AU (1 AU is an Astronomical Unit – the average distance between the Earth and the Sun) in diameter, how many times larger is a 10 pc diameter GMC than the solar system? (1 AU = 1.496×10^{13} cm). *A – 10 pc = 3.086×10^{19} cm. Therefore 10 pc = 2.06×10^{6} AU, or 5222 times larger than the solar system.*

2) Examine Figures 3.2 and 3.3 (optical images of interstellar clouds). How many different types of structures can you find? *A – Clumpy structures, filamentary structures, plumes, dust lanes, etc....*

3) Examine Figure 3.2, the optical image of the Horsehead nebula region in Orion. Which numbered area or areas do you think would be the most likely places for stars to form? *A – Two regions: Region #1 – the GAS in NGC 2024, which is dense ($n(H_2) > 10^5 cm^{-3}$), and Region #4, the gas in NGC 2023. Region #2 is dust, not gas. Region #3 is already a star which has evaporated most of the immediately surrounding gas. Region #5 is not very dense, and Region #6 is, again, dust, not gas.*

4) Can you think of a situation in real-life whereby spinning something causes it to flatten out and become disk–like? *A – Pizza dough is a good example.*

5) Can you think of any evidence that our sun formed at the center of a spinning disk? (Hint – how do the planets orbit the Sun?) *A – Astronomers believe that our solar system did, indeed, form from a spinning disk which has long since disappeared. The facts that all of the planets orbit in the same direction and in the same orbital plane (i.e. in a disk) point towards a disk origin.*

6) What is the mass that is needed for a cloud to begin collapsing under its own gravity if the gas has a temperature of 20K and a density of 10^5? *A – Using the Jean's Mass formula: $M_J = 28.3\ M_{\odot}$.*

7) Which gas will cool faster: Gas #1 which has a density of 100 particles per cubic centimeter, or Gas #2 which has a density of 10^6 cm^{-3}? *A – Gas #2. The higher density means that more collisions will occur resulting in more de–excitations. Of course, this gas also heats up more easily....*

8) The Orion nebula is visible with your naked eye (or a pair of binoculars) in the Winter/Fall sky. Try to find it on a clear night.

CHAPTER 4 – THE BASICS OF RADIO ASTRONOMY.

4.1. RADIO TELESCOPES.

Since radio waves are just another form of light (with wavelengths > 10^{-4} m) they follow the same laws of reflection that apply to optical light. Therefore, one can construct a radio telescope from reflecting surfaces which are analogous to the mirrors of an optical telescope. In general, a radio telescope operates as follows: the incoming radio waves reflect off the primary surface (called the *dish*) and get focused onto a smaller reflecting surface (called a *sub–reflector*). The sub–reflector re–focuses the radio waves, sends them through a small hole at the center of the primary dish, and into a receiver which detects the radio waves. This type of telescope arrangement is called a *Cassegrain telescope*, and is illustrated in Figure 4.1.

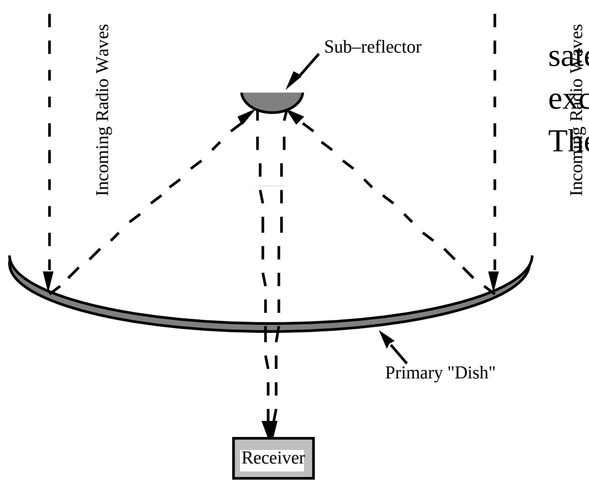


Figure 4.1 – An illustration of a Cassegrain Radio Telescope. The incoming radio waves reflect off the primary dish (a parabolic reflecting surface) and get focused onto the sub–reflector. The sub–reflector re–focuses the radio waves, sends them through a small hole at the center of the primary dish, and into a receiver which detects the radio waves.

Radio telescopes often look like satellite dishes (see Figures 4.2 and 4.3) except that they are usually much larger. There are three reasons for this:

1) Since the wavelength of a radio wave is large, its energy is small. Therefore, one requires a large dish in order to detect the weak, low energy radio emission from space.

2) A large diameter dish is needed in order to achieve good *resolution.* Resolution (or the *resolving power* of a telescope) is a measure of the smallest detail one can see from a distance. For example, suppose the distance measured between two stars is 1 *arcsecond* (1 *degree* = 60 *arcminutes* = 3600 arcseconds). If a telescope's resolution is less than 1 arcsecond, you will see two separate stars (astronomers say the stars are *resolved*). If the telescope's resolution is greater than 1 arcsecond then the two stars will appear as a large fuzzy blob and we say that the stars are *unresolved*. The resolving power is calculated by the formula:

$$RP = 206265\ {}^{\lambda}\!/_{d}$$

where RP is the resolving power of the telescope in *arcseconds* , λ is the wavelength of the light being detected and d is the diameter of the telescope. λ and d can be in any units but they must both have the same units (e.g. both measured in meters or centimeters etc.). For example, if an optical telescope with a diameter of 1 meter is collecting light with $\lambda = 6 \times 10^{-7}$ meters, it has a resolving power of 0.124 arcseconds. In order for a radio telescope (collecting light with $\lambda = 0.01$ meters) to have the same resolving power it would need a dish with a diameter of 16,666 meters!

Figure 4.2 – A picture of the 10.4 meter diameter Caltech Submillimeter Observatory (CSO) – a radio telescope on Mauna Kea, Hawaii. This telescope is constructed of numerous hexagonal shaped panels which comprise the primary dish. Notice the sub–reflector, which is supported above the primary dish by four support legs (only three of which are visible), and the Cassegrain hole at the center of the dish. The CSO is operated by the California Institute of Technology.

Figure 4.3 – A picture of the giant 300 meter diameter radio telescope in Arecibo, Puerto Rico. The surface of this telescope is composed of wire mesh. This telescope is not a Cassegrain telescope, but is a *Prime Focus* telescope, so called because the large triangular object suspended from the three pedestals is not a sub–reflector but is where the radio receivers are located. Note that the dish is large enough to contain **three football fields** laid out end to end. The Arecibo Observatory is operated by the National Astronomy and Ionisphere Center at Cornell University.

3) It is easier to make a large radio telescope than it is to make a large optical telescope – so why not do it? As a rule–of–thumb a reflecting surface must be accurate to within a factor of λ/40 or the reflections will be distorted. This means that for the same optical telescope as in #2 (above), the mirror must be accurately polished to within 1.5×10^{-6} cm (or 5.9/10,000,000 of an inch)! Our radio telescope, however, only needs to be accurate to within 2.5×10^{-4} cm (or 9.8/10,000 of an inch).

The similarities between radio telescopes and optical telescopes end when one begins to describe the devices which detect the radiation. Optical telescopes use instruments called *Charge Coupled Devices (CCD)* to detect the incoming photons of light. Radio telescopes, on the other hand, place antennae at the focus of the telescope. The incoming radio waves strike the antenna and induces a current. The subsequent current is then processed into information which can be analyzed by computers (Figure 4.4). A very similar process occurs when you listen to your car radio (Figure 4.5). The radio waves induce a current in the car's antenna. The current travels into the radio where it is processed into sound. The instruments placed at the focus of a radio telescope, which contain the antennae are called *receivers*. Just as an optical astronomer chooses a CCD which is most sensitive to the wavelength of light he is trying to detect, the radio astronomer tunes the receiver to amplify the specific wavelengths she wants to detect.

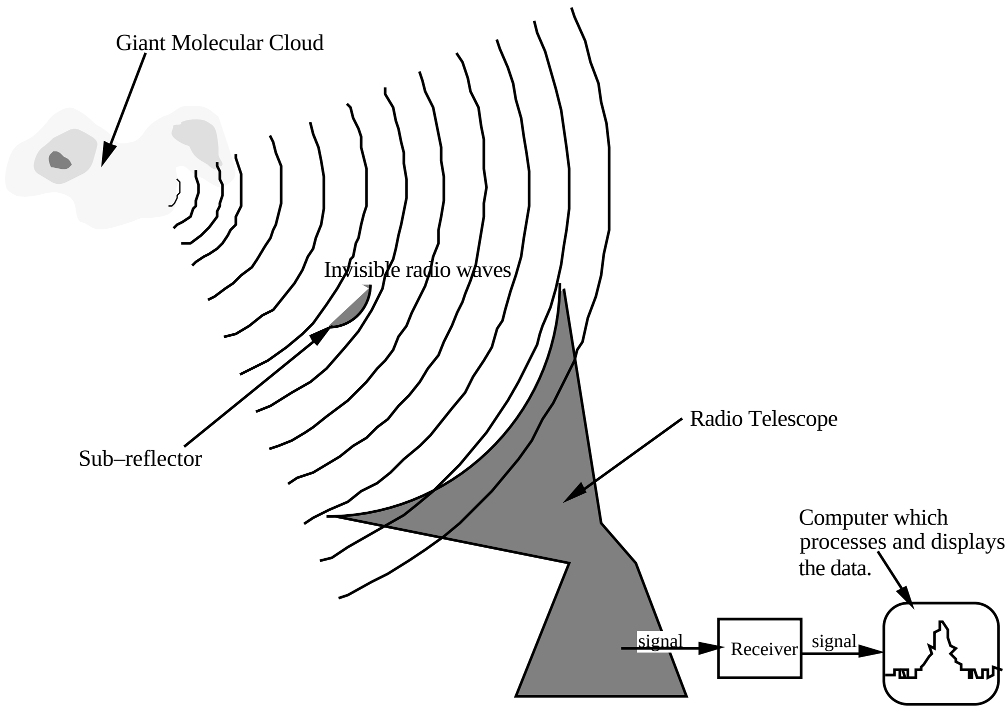


Figure 4.4 – Illustration of a radio telescope detecting radio waves from a Giant Molecular Cloud. The radio waves are collected by the primary dish, and reflect off of the sub–reflector which focuses the radio waves onto the receiver. The receiver contains a tiny antenna which produces an electric current when struck by the radio waves, and a series of electronic components which amplify and filter the signal. The signal is processed into information which can be analyzed by astronomers.

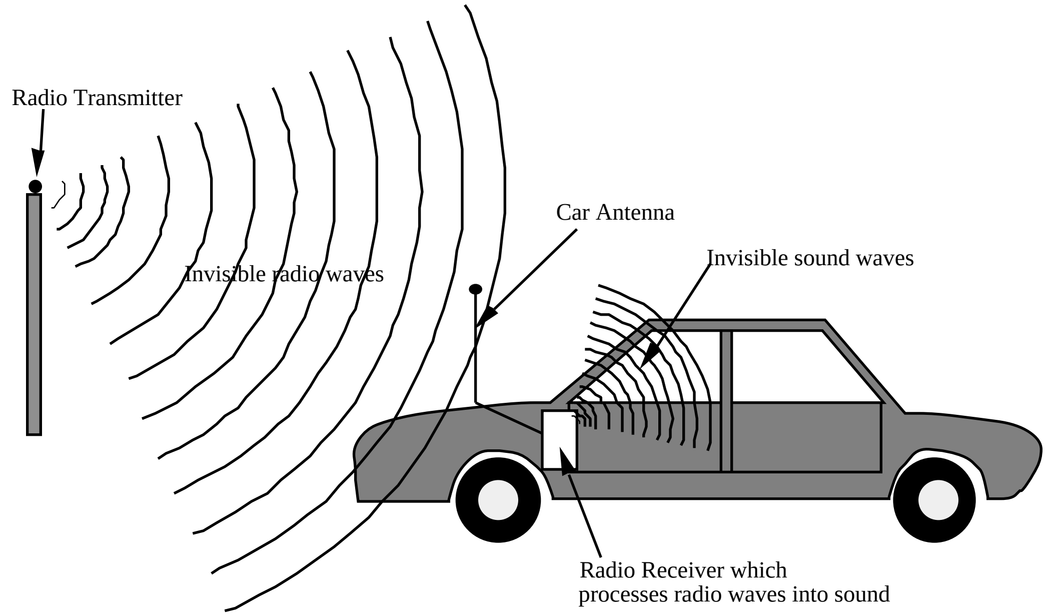


Figure 4.5– Illustration of how a car radio operates in a fashion similar to a radio telescope. The radio waves from the transmitter tower strike the car's antenna and induce a current. The current then travels to the radio where it is amplified and processed into sound which you can listen to.

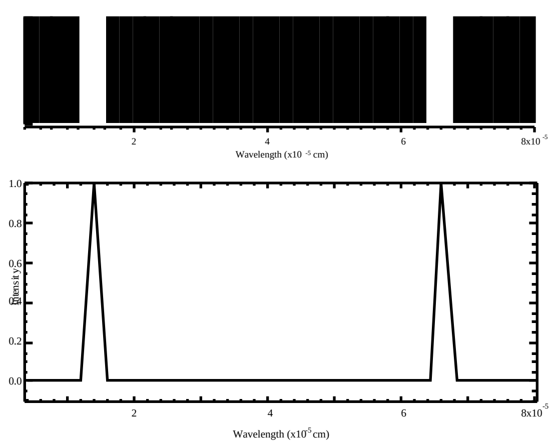


Figure 4.6 – Two methods with which to display a Hydrogen spectrum. The top plot shows what part of the optical spectrum of Hydrogen actually looks like (the same as Figure 2.6) – two bright narrow lines (wavelengths of $1.2x10^{-5}$ cm and $6.6x10^{-5}$ cm respectively). If we plot the intensity of the spectrum as a function of wavelength (bottom plot), we see that the intensity is 0 until we encounter the first bright line at $\lambda = 1.2x10^{-5}$ cm at which point we see an intensity peak. The intensity then quickly drops back to 0 until we encounter the next bright line at $\lambda = 6.6x10^{-5}$ cm at which point we see another intensity peak.

4.2. RADIO SPECTROSCOPY.

As with optical light, light at radio wavelengths can be passed through a spectrograph (or *spectrometer*) and spread out according to frequency. However, since we cannot see the radio emission with our eyes, we use computers to display the radio spectra.

Returning for the moment to optical spectra, Figure 4.6 shows the same Hydrogen spectrum as shown in Figure 2.6 (Chapter 2) and demonstrates that one can also display a spectrum by plotting intensity as a function of wavelength. Since the Hydrogen spectrum (top of Figure 4.6) essentially appears as two bright lines, plotting the intensity yields two sharp spikes (bottom of Figure 4.6).

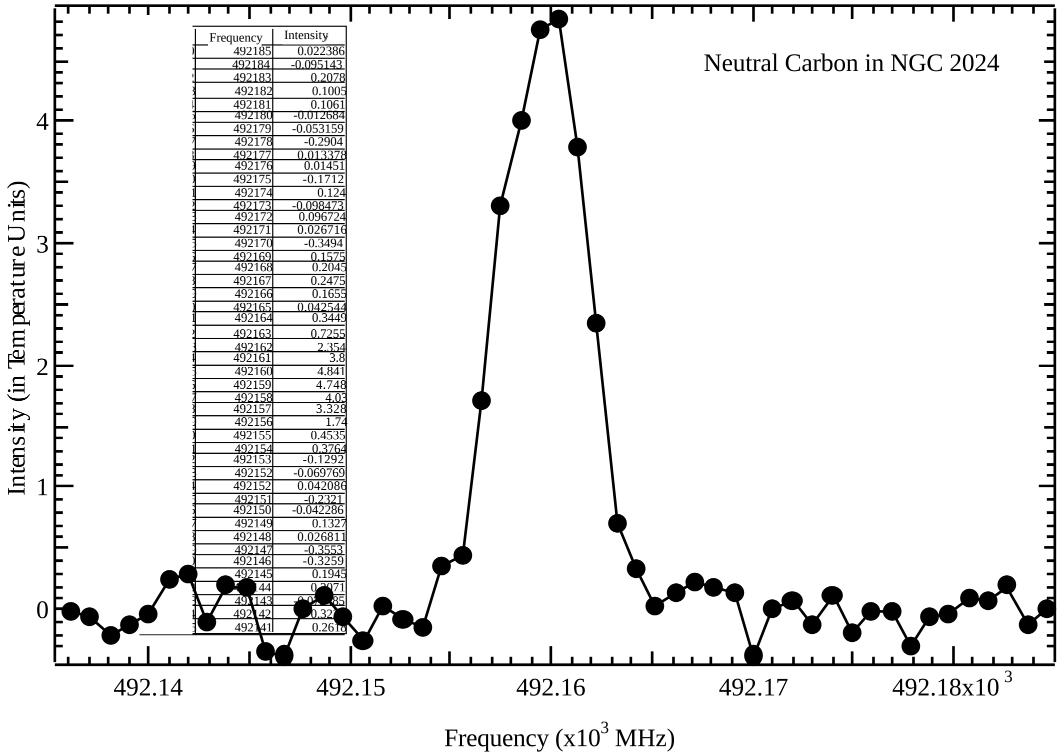


Figure 4.7 – Spectrum of the neutral carbon line in NGC 2024 (a Molecular cloud in Orion; see Figure 3.2). The Numbers in the table are the frequency and Intensity (in temperature units) of the spectral line as measured by the computer. The solid circles plot the numbers listed in the table.

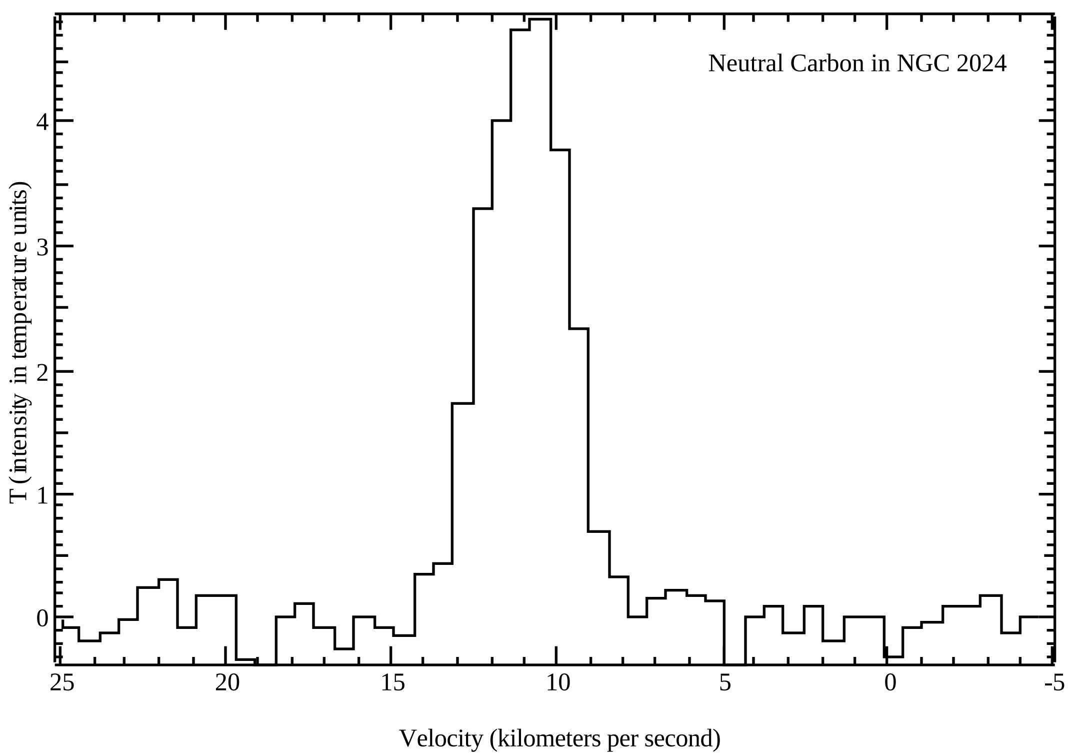


Figure 4.8 – Spectrum of the neutral carbon line in NGC 2024 (a Molecular cloud in Orion; see Figure 3.2). The intensity which is plotted in temperature units (degrees Kelvin) is shown as a histogram. The X-axis is velocity instead of frequency or wavelength. Since the spectral line peak at approximately 11 km/s the GMC is moving away from us at this speed. Each measurement is separated by 0.5914 km/s, so we say that the *velocity resolution* is 0.5914 km/s. **Note** that the velocity is plotted as decreasing from left to right. This was done in order to directly compare Figure 4.7 with 4.8.

We can plot radio spectra in exactly the same fashion with which we plot the optical spectra in Figure 4.6. After the radio waves have been detected and processed by the receiver, the signal is passed through a spectrometer which obtains a radio spectrum. The radio spectrum is then measured by instruments which are sensitive to radio wavelengths and produces a list of wavelengths (or usually frequencies) and intensities which can be plotted by the computer. Figure 4.7 shows a list of frequencies and intensities that the computer reads from the radio spectrometer, and illustrates how the corresponding radio spectrum would look. It is important to note that in spite of the fact that the intensity of radio spectra is often displayed as a *temperature*, this is **not an actual temperature**, but simply another unit of intensity. This temperature intensity is measured in units of degrees Kelvin. Figure 4.8 displays the most common way of plotting radio spectra – using a histogram instead of a "connect–the–dots" type of plot shown in Figure 4.7. In addition, the X–axis of Figure 4.8 has been transformed to velocity units (kilometers per second) instead of the more familiar frequency or wavelength units. Radio astronomers use this unit since it is a direct measurement of how fast the molecular cloud is moving toward or away from us.

As a final note, astronomers often measure other properties of the spectral line other than just its intensity (or temperature). These properties are measured by fitting a *Gaussian* profile to the spectral line which is done with the aid of a computer. A Gaussian profile is more commonly known as a *Bell Curve* – a curve which peaks in the center and falls off symmetrically on both sides of the center according to a mathematical formula. The quantities that astronomers measure from the Gaussian fit to the spectral line are :

1) *Peak Temperature (T)* – The height (or intensity) of the spectral line at the peak.
2) *Velocity (V)* – The velocity at the center of the line.
3) *Full Width at Half Maximum (FWHM)* – The FWHM is measured as the full width of the line when measured halfway between 0 and the maximum intensity of the line.
4) *Integrated Intensity (Tdv)* – This quantity is simply the peak temperature of the line times its FWHM, which is the area under the spectral line (which can be calculated by summing up the intensity from each measured velocity and then multiplying by the velocity resolution). Therefore, the units of integrated intensity are K km/s (Kelvin kilometers per second) and is usually written at Tdv.

Figure 4.9 illustrates points 1 through 4 above, and shows a Gaussian fit to the neutral carbon line in NGC 2024 (originally shown in Figure 4.8). The peak temperature

(T) is 5.0 K, the Velocity (V) is 10.7 km/s, the FWHM is 3.0 km/s and the integrated intensity (Tdv) is 16.2 K km/s.

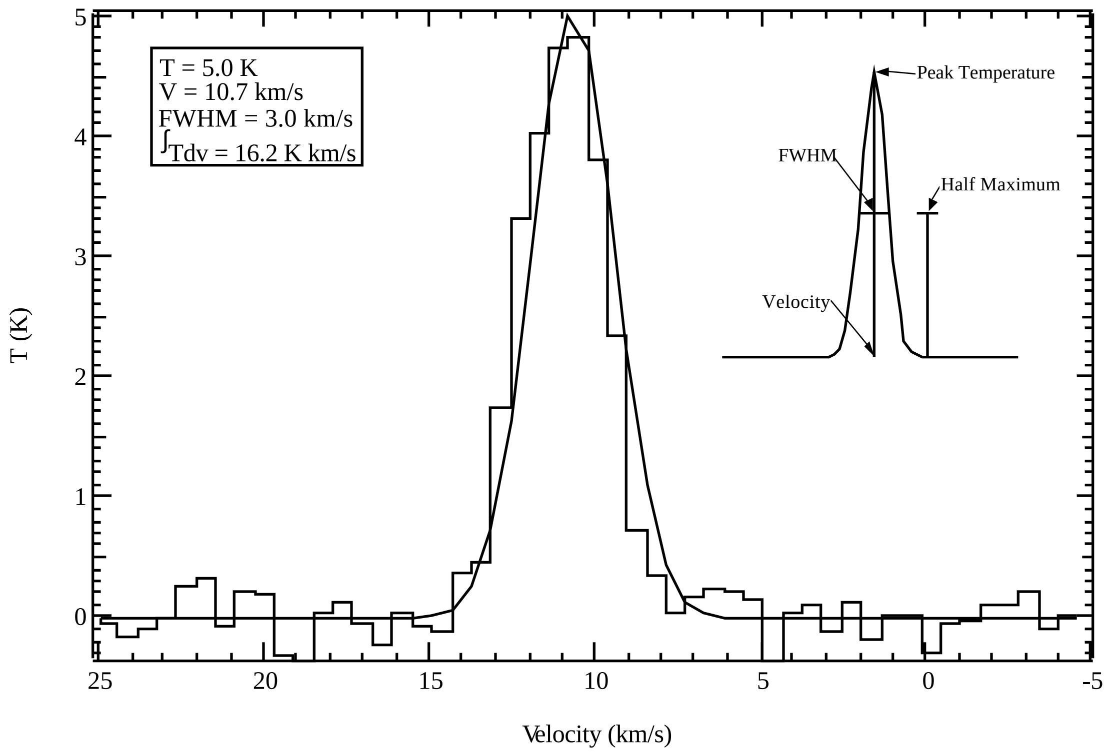


Figure 4.9 – Spectrum of the neutral carbon line in NGC 2024 (a Molecular cloud in Orion; see Figure 3.2). The parameters determined from fitting a Gaussian profile to the spectral line are listed in the box in the upper left hand corner. The inset figure at the upper right explain what these Gaussian properties are.

4.3. FOOD FOR THOUGHT – QUESTIONS FOR CHAPTER 4.

1) What is the resolution of the Caltech Submillimeter Observatory if it is operating at a frequency of 492 GHz (the frequency of neutral carbon)?

A – $\lambda = c/\nu = 3x10^{8}$ *m/s/492x*10^{9} *Hz =* $6.1x10^{-4}$ *m*

$d = 10.4$ *m*

Therefore : $RP = 206265 \times 6.1x10^{-4} / 10.4$

$RP = 12.1$ *arcseconds*

2) What is the resolution of the Caltech Submillimeter Observatory if it is operating at a frequency of 230 GHz (the frequency of one of the ^{13}CO spectral lines)?

A – $RP = 25.9$ *arcseconds*

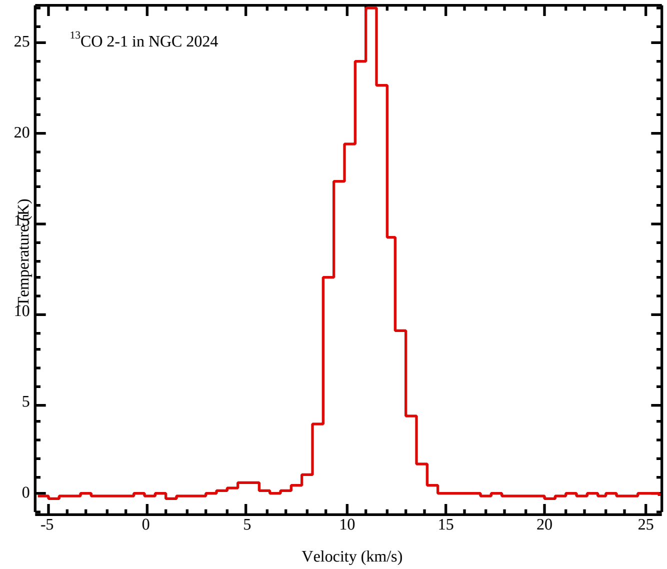
3) What is the resolution of the Arecibo Observatory if it is operating at a frequency of 1.4 GHz (the frequency of atomic Hydrogen's spectral line in the radio regime)?

A – $RP = 147$ *arcseconds.*

4) The following table lists the velocities and temperatures of the ^{13}CO 2-1 spectral line (230 GHz) in NGC 2024. Plot the spectrum and calculate : a) the peak temperature, b) the velocity of the line, c) the FWHM of the line, d) the integrated intensity of the line.

Velocity km/s	**T Degrees K**	**Velocity km/s**	**T Degrees K**	**Velocity km/s**	**T Degrees K**
-5.43504	-0.028409	6.19155	0.1391	17.8181	-0.031563
-4.90656	-0.1562	6.72003	0.1904	18.3466	-0.023597
-4.37808	-0.036146	7.24851	0.5224	18.8751	-0.118
-3.8496	-0.1424	7.77699	1.09	19.4036	-0.069492
-3.32112	0.085308	8.30547	3.972	19.9321	-0.1589
-2.79263	-0.058789	8.83395	11.98	20.4605	-0.041967
-2.26415	-0.1418	9.36243	17.43	20.989	0.052823
-1.73567	-0.082897	9.89091	19.48	21.5175	-0.020644
-1.20719	-0.054747	10.4194	24.04	22.046	0.068671
-0.678711	0.092351	10.9479	26.97	22.5745	-0.080843
-0.15023	-0.026595	11.4764	22.7	23.1029	0.093078
0.378252	0.053703	12.0048	14.27	23.6314	-0.044489
0.906733	-0.1681	12.5333	9.034	24.1599	-0.061529
1.43521	-0.09496	13.0618	4.375	24.6884	0.053932
1.9637	-0.033119	13.5903	1.682	25.2169	0.056626
2.49218	-0.011058	14.1188	0.528	25.7453	-0.028278
3.02066	0.011743	14.6472	0.1295		
3.54914	0.1555	15.1757	0.094325		
4.07762	0.3474	15.7042	0.087797		
4.6061	0.6194	16.2327	-0.0028012		
5.13458	0.6873	16.7612	-0.051		
5.66306	0.1743	17.2896	-0.0053527		

A – The Spectrum should look something as follows:



The requested spectral line parameters are :

Quantity	Gaussian Fit	From Table
Peak Temperature (K)	26	26.97 [1]
Velocity (km/s)	10.7	10.9479 [2]
FWHM (km/s)	3.1	3.2 [3]
Integrated Intensity (K km/s)	84.8	84.9 [4] or 86.3 [5]

1 The maximum value of T in the table.

2 The velocity of the maximum value of T in the table.

3 Half of the maximum T is 13.485 K. Although we do not have any entries in the table with exactly this value, we can see that 13.485 K will occur between 8.83395 km/s and 9.36243 km/s, and again between 12.0048 km/s and 12.5333 km/s. We can, therefore, estimate that 13.485 K will occur at approximately 8.9 km/s and again at 12.1 km/s. Therefore the FWHM is 12.1 - 8.9 ~ 3.2 km/s (very close to value derived from the Gaussian fit!).

4 We have calculated the integrated intensity between 3.02066 km/s and 15.7042 km/s – two points where the line temperature has dropped to approximately 0 K. Summing all temperatures listed in the table that fall between these two velocities we obtain approximately 160.65 K. However, we must multiply by the velocity resolution which is 0.52848 km/s. Therefore, the integrated intensity is ~ 84.9 K km/s (again very close to the value derived from the Gaussian fit).

5 Multiple the peak temperature by the FWHM = 26.97 x 3.2 = 86.3 K km/s.

CHAPTER 5 – SWAS IN MORE DETAIL.

5.1 SPACECRAFT DESIGN.

SWAS is dedicated to the study of star formation and interstellar chemistry. To carry out this mission, SWAS will survey dense ($n(H_2) > 10^3$ cm^{-3}) molecular clouds within our galaxy five astrophysically important species: H_2O, $H_2{}^{18}O$, O_2 , CI, and ^{13}CO. By observing these lines SWAS will test long-standing theories that predict that these species are the dominant coolants of molecular clouds during the early stages of their collapse to form stars and planets.

5.1.1. About SWAS

The SWAS spacecraft is an orbiting, off–axis, Cassegrain radio telescope. Its primary dish is a 68 x 53 cm polished aluminum primary mirror. SWAS's low resolution of 3.2 x 4.0 arcminutes at 551 GHz and 3.6 x 4.5 arcminutes at 492 GHz will allow us to obtain maps of giant and dark clouds that cover a large area of the sky (i.e. greater than 1 arcminute x 1 arcminute). SWAS's instrumentation weighs 93 kg and attaches to the top of the spacecraft structure as a single module. The total spacecraft mass is 286 kg. SWAS will be operated in a 600 x 650 km elliptical orbit with a 70 degree inclination. Figure 5.1 shows an artist's conception of what SWAS will look like in orbit.

Four deployable, fixed solar panels and one body-mounted panel contain 3.4 square meters of solar cells and provide 230 Watts of power per orbit that is distributed to the spacecraft and instrument. The orbit average power consumption of the spacecraft hardware is 123 Watts. The instrument consumes 59 Watts. Note that despite all of SWAS's instruments, this is less power than that consumed by a 60 Watt light bulb!

SWAS is stabilized along all three axis and can point on a target with a 38 arcsecond accuracy (a small fraction of its resolution). The spacecraft will point the science instrument at typically 3-5 targets per orbit. Target selection is constrained such that the solar arrays always face within +15 degrees of the Sun, except during eclipse. The spacecraft can move from an on-source target position to an off-source instrument calibration position up to 3 degrees away in less than 15 sec. This movement occurs approximately every 40 sec to ensure accurate calibration of the data.

Attitude control, including pointing and nodding are accomplished by using three magnetic-torquer coils, one digital Sun sensor, five coarse Sun sensors, four reaction wheels, one magnetometer, three inertial gyros, and a high accuracy optical CCD star tracker. Since many of the objects to be studied by SWAS are optically invisible, pointing of the SWAS telescope is achieved by identifying and tracking visible stars in the vicinity of the regions of interest. As SWAS orbits the Earth, a star tracker is used to identify star fields and maintain lock on these fields when SWAS is taking data. SWAS will typically observe three to five astronomical objects per orbit. SWAS will orbit the Earth every 97 minutes.

The data systems for the SWAS mission contains 110 Mbytes of bulk memory. It utilizes the MIL-STD-1553 data bus to communication with the subsystems and the instrument. Instrument data is collected at approximately 12 kbps average rate. Dual quadrifilar antennas are used for ground communications. The stored data is transferred to the ground at 1.8 Mbps data rate. Commands are uplinked at 2 kbps transmission rate.

SWAS is currently scheduled for an October 1996 launch, with an mission lifetime of two years. SWAS will be launched from the Western Test Range, Vandenberg Air Force Base, in Lompoc, California, using a winged Pegasus-XL launch vehicle. The Pegasus-XL launch vehicle, built by Orbital Sciences Corporation, is a three-stage, solid-propellant booster system carried aloft by an L-1011 jet aircraft and released from the aircraft at an altitude of about 40,000 feet and an airspeed of Mach 0.8. The 630-pound (286 kilogram) SWAS observatory then will be inserted into an orbit with an altitude of 370 miles (600 kilometers) above the Earth and inclined 70 degrees to the equator. NASA's Wallops Flight Facility in Virginia and a NASA-developed Transportable Orbital Tracking Station (TOTS) placed at Poker Flat, Alaska, will serve as the primary ground stations.

5.1.2. The Signal Detection Subsystem

The SWAS instrument is comprised of two major subsystems: (1) the signal detection subsystem consisting of two radio receivers which operate at submillimeter wavelengths built by Millitech Corporation, and (2) a spectrometer, provided by the University of Cologne in Germany. Figure 5.2 is a cut–away drawing of SWAS’s instrument module.

The principle by which the SWAS instrument operates is simple: light collected by the 68 x 53 cm polished aluminum primary mirror is split in two, with each half being brought to a focus within each of two radio receivers. These receivers, will be passively cooled (meaning that no refrigerators are used to artificially cool the system) to approximately 170 K to enhance their performance. The receivers and the following amplifier circuits select a radio frequency (RF) band within ±350 MHz of the incoming 550 GHz and 490 GHz astronomical radiation, convert the signals to the 1.4 to 2.8 GHz frequency range, and input them to the spectrometer. SWAS will have the ability to simultaneously observe the water, molecular oxygen, atomic carbon, and carbon monoxide lines with a velocity resolution of less than 1 km/s.

Figure 5.1 — (Next page) An artist's conception of what SWAS will look like in orbit. The solar panels are pointed towards the Sun, but the dish (at the top) is pointed away from both Earth and the Sun. The three cylindrical objects just below the dish are the Winston Cones which help to passively cool the instrumentation.

Figure 5.2 — A cut–away drawing of the instrument section of SWAS. The incident radio waves reflect off of the primary dish onto the "chopping Secondary Mirror" which is the sub–reflector. From there, the radio waves are focused into the passively cooled submillimeter receivers. From there, the processed radiation is sent to the acousto–optical spectrometer. The Cold radiators (or Winston Cones) passively cool the system by allowing heat, produced by the instrumentation and the various electronic boxes, to effectively escape into space. The star tracker allows the spacecraft to find and track giant molecular cloud targets by searching for and locking on optical guide stars.

The spectrometer is a device called an *Acousto–Optical Spectrometer (AOS)*, which is quite a clever instrument. Inside of the acousto-optical spectrometer the RF signals are converted to acoustic (sound) waves within a crystal, causing pressure waves to travel along this crystal. When illuminated by laser light, the alternating patterns of compression and expansion within the crystal acts like the finely spaced lines of a grating (or a prism) causing the laser light to be dispersed along one dimension with intensity variations along this direction that are proportional to the intensity. In this way, the acousto-optical spectrometer is able to dissect the radiation incident on the SWAS telescope into its constituent frequencies and intensities, much as a prism disperses white light into a spectrum of colors. The dispersed laser light is imaged onto a 1400-pixel liner charge-coupled device (CCD) array with each pixel corresponding to 1 MHz of resolution and the counts in each pixel corresponding to the associated intensity. Figure 5.3 is a block diagram illustrating the signal detection subsystem.

Every 2 seconds the data from the spectrometer, along with housekeeping data (temperatures, voltages, currents, etc.), are transferred to the spacecraft data storage system. Data are transmitted to NASA ground stations twice per day and, within 24 hours of its receipt at these ground stations, these data are received at the Smithsonian Astrophysical Observatory's SWAS Science Operations Center. The science

SWAS SIGNAL DETECTION SYSTEM: FUNCTIONAL BLOCK DIAGRAM

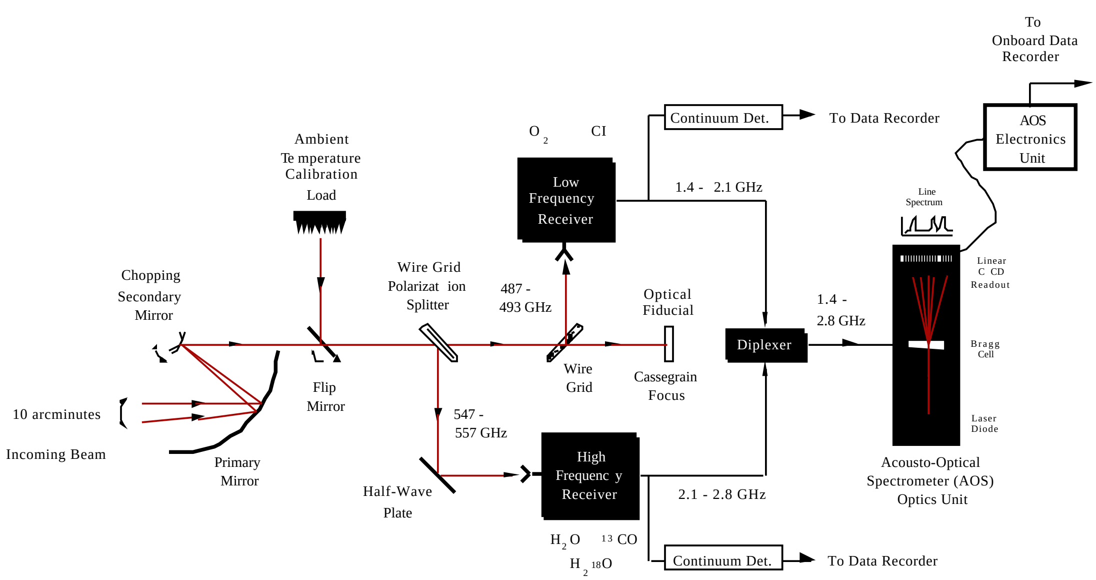


Figure 5.3 — Block Diagram of SWAS's signal detection subsystem. Radio waves enter from the left via the primary and secondary mirrors (dishes). The radiation is then split into two different receivers through the use of wire grids which reflect some of the radiation and allow the rest to pass through unhindered. The receivers detect and amplify the signals and then send them into a diplexer, which re-combines the radio signals and sends them into the Acousto–Optical Spectrometer. Finally the information from the AOS is recorded and displayed by a computer.

content of the data is analyzed and new astronomical targets are selected for observation.

5.1.2. The Thermal Control System

Radio receivers operate best when cold. However, the operation of the receivers unavoidably creates heat. Therefore, we need to remove the heat produced and keep SWAS as cold as possible. One option is to actively cool (or refrigerate) the instruments by bathing them in cryogens (like liquid nitrogen at 77 K). Cryogens, however, are expensive and eventually evaporate, significantly reducing the life of the mission. The other option is to passively cool the instrument, meaning that no cryogens are employed.

SWAS is passively cooled, relying on a number of techniques :

1) SWAS avoids pointing near the Sun. SWAS's software has been designed to automatically avoids pointing anywhere within 75˚ of the Sun. This means that no solar radiation will strike the dish and reflect into the instruments, causing them to heat up.

2) SWAS avoids pointing at the Earth as well. The Earth avoidance angle, however, is only 35˚.

3) SWAS employs three Winston *Cones* which allow the produced heat to effectively radiate into space.

5.2. FOOD FOR THOUGHT – QUESTIONS FOR CHAPTER 5.

1) How many different branches of science can you think of that have been included in the conception, design, production, launch, and maintenance of SWAS?

A – Astronomy, Chemistry, Physics, Engineering, etc..........be creative!

GLOSSARY OF TERMS.

Acousto–Optic Spectrometer (AOS) – A device which produces a spectrum by producing an acoustic wave in a crystal, and then shining an optical laser through the crystal.

Arcminute – 1/60th of a degree.

Arcsecond – 1/60th of an arcminute = 1/3600th of a degree.

C – The speed of light. 30,000,000,000 (or 3×10^{10}) centimeters per second (cm/s).

CCD – *See Charge Coupled Device.*

CI – Neutral carbon. One, single, unionized carbon atom.

CO – Carbon Monoxide. Composed of one carbon and one oxygen atom.

^{13}CO – (pronounced thirteen C O). A rarer isotope of CO. The oxygen is “normal” but the carbon atom contain 6 protons and 7 neutrons, instead of 6 protons and 6 neutrons for the “normal” carbon atom.

Cassegrain – An arrangement of mirrors in a reflecting telescope whereby light is reflected by a second mirror to a point behind the primary mirror.

Charge Coupled Device – An array of electronic detectors of electromagnetic radiation, used at the focus of a telescope (or camera lens). A CCD acts like a very sensitive photographic plate.

Density – *See $n(H_2)$.*

De–excitation – The process of removing from an electron an amount of energy greater than it possesses in its lowest energy (ground) state. This process causes an electron to jump form a higher energy level to a lower energy level, releasing a photon.

Dish – The main reflecting surface of a radio telescope.

Dyne – The metric unit of force; the force required to accelerate a mass of 1 gram in the amount of 1 centimeter per second per second.

Erg – The metric unit of energy; the work done by a force of one dyne acting through a distance of 1 centimeter.

Electromagnetic spectrum – The whole range of electromagnetic radiation with wavelengths from 0 to infinity.

Energy Level – A particular level, or the amount of energy possessed by an electron, above its ground state.

Excitation – The process of imparting to an electron an amount of energy greater than it possesses in its lowest energy (ground) state. This process causes an electron to jump form a lower energy level to a higher energy level.

Frequency – The number of cycles per second of any periodic motion. With radiation, this is the number of waves that cross a given position in one second. Usually denoted by the Greek letter ν (pronounced nu). *see Hz.*

Full Width at Half Maximum (FWHM) – The width of a Gaussian shaped spectral line measured at a height equal to half of the line’s maximum intensity.

Gaussian – A "Bell Curve". A line profile which peaks in the center and decreases symmetrically on both sides of the peak. The decrease follows a rigid mathematical formula.

GHz – A Gigahertz or 10^9 Hertz. *see Hz.*

Ground State – The lowest possible energy state (or level) of an electron in an atom.

h - *see Planck's constant*

Hz – Hertz. The unit of frequency indicating the number of cycles per second.

H_2 – A Hydrogen molecule. Composed of two Hydrogen atoms.

H_2O – Water. Composed of 2 Hydrogen atoms and one oxygen atom.

$H_2{}^{18}O$ – A rarer isotope of water.

Jean's Mass - M_J, the mass required for a cloud to begin collapsing under the force of its own gravity

K – A unit of temperature called the Kelvin. This scale is sometimes called the absolute scale since 0 K is also known as "absolute zero". 0 K = –273˚ C (Celsius) = –459˚ F (Fahrenheit) and the temperature at which all molecular motion ceases.

Luminosity – The rate of electromagnetic energy into space by a star or other object.

$L_\odot$ – A solar luminosity, equal to the luminosity of the Sun of 3.83×10^{33} ergs/s

Mass – A measure of the total material in a body.

$M_\odot$ – A solar mass, equal to the mass of the Sun (2×10^{33} grams).

Molecular Cloud – A giant interstellar cloud of molecular gas in which stars form. Typical molecules are H_2, CO, CS...and hundreds more.

$n(H_2)$ – A measurement of gas density most often used by radio astronomers. It is literally translated as the number of Hydrogen molecules (H_2) per cubic centimeter (cm^{-3}). For example, a gas density of 10,000 hydrogen molecules per cubic centimeter would be written as $n(H_2) = 10^4\ cm^{-3}$.

Nuclear Fusion – The process which powers a star. Two atom fuse together to form a larger heavier atom (like 2 hydrogen atoms fusing into Helium). This process releases a tremendous amount of energy.

O_2 – Molecular oxygen. Composed of two oxygen atoms.

Photon – A particle of light.

Planck's constant – The constant used to determine the energy of radiation given its frequency (6.626×10^{-27} erg/s).

Primary – The main reflecting surface of any telescope.

Prime Focus – The point in a telescope where the primary mirror focuses the light.

Proto–star – The stage of star formation just before the onset of nuclear fusion which defines the birth of a real star. A proto–star produces and releases energy, but not from nuclear reactions.

Radiation – A mode of transportation whereby energy is transmitted through space; also the energy itself either as a wave or a particle.

Radio Telescope – A telescope specifically designed to collect and detect radio waves instead of optical light.

Spectrum – The array of colors or wavelengths obtained when light from a source is dispersed, as in passing it through a prism or a grating.

Speed of Light – *See C.*

Spectrograph – A device for creating and recording a spectrum.

Spectrometer – *See Spectrograph.*

Sub–reflector – The secondary reflecting surface of a telescope. This is usually much smaller than the primary and focuses the light onto the detectors.

Temperature (intensity) – An intensity scale used in radio astronomy whereby the intensity (or brightness) is measured as a temperature. This is not the physical temperature of the molecular gas which is measured.

Wavelength – The distance between successive crests (or troughs) of any periodic motion. Usually denoted by the Greek letter λ (pronounced lambda).

ν – *see frequency.*

λ – *see wavelength.*